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Impact of Climate Change on the Water Resources, Lake Powell, United States

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Abstract This case study examines the impacts of climate change on water resources at Lake Powell, USA, using a comprehensive methodology combining data analysis through regression and system dynamics modeling. Through regression analysis, historical data is analyzed to identify trends and relationships between climate change factors and their impact on water resources. A system dynamics model is then used to simulate reservoir dynamics illustrating the effects of inflow and outflow on water reservoir depletion. The results from both methods reveal the challenges of current water management regulations and policies to address the risks-posed by climate change at Lake Powell. Therefore, this case study highlights the urgent need for sustainable water management policies at Lake Powell. Underscoring the seriousness of the problem overhaul of existing strategies, the research argues for proactive measures to mitigate the effects of climate change. The study provides policymakers and water resource agencies with significant insights and recommendations sustainable utilization of this essential resource.

Keywords: *climate change, Lake Powell, regression method, system dynamic, water resources*

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1. Introduction

Climate change remains a major concern globally due to its significant impact on the environment and human life. Recent studies [1,2,3] have highlighted effects of changing climate on water resources and supply as a major consequence including shifting precipitation patterns [4,5,6,7], increase evaporation rates [8], enhanced drought [9] increased snowmelt [10,11,12,13], flooding [13] which are all affecting water availability and quality [6] [14,15,16].

The effects of climate variations on water supplies have been addressed by various organizations, governments, and scientific institutions globally [17,18]. The Intergovernmental Panel on Climate Change (IPPC) has published several reports about how climate change affects water resources. The European Union (EU) has developed the water framework directive, which sets out a framework for sustainable water management in the EU [19] The World Bank has also launched several initiatives aimed at promoting sustainable water management and improving water access in developing countries. The United Nation reported the world would need to invest extensively in infrastructure over the next 15 years, spending over $90 trillion by 2030 [17].

The available of knowledge on the consequences of climate change on global water supply indicates that the issue remains a significant concern and these effects are predicted to worsen with time.

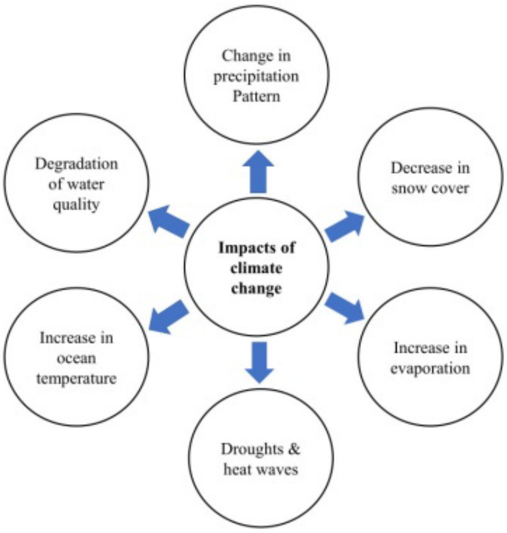

Figure 1. Illustrating impacts of climate change

Figure 1 summarizes findings of several research on the effects of climate change in many regions, based on changing precipitation, melting glaciers, and droughts that influence water supplies in terms of quantity and quality [4] [8,9] [11] [16]. The recent Global Climate Risk Index evaluates and ranks all nations and regions that have experienced extreme weather connected to climate change (storms, floods, heat waves etc.). It has been determined that Puerto Rico, Burma, and Haiti are the most afflicted nations. Philippines, Mozambique, and the Bahamas take second, third, and fourth place, respectively [20]. Between 2000 and 2019, Table 1 lists the 10 nations most affected by the climate risk index.

There have been numerous efforts [3,4,5] [21] to address the issue, including the development of policies and initiatives aimed at promoting sustainable water management, reducing greenhouse gas emissions, and promoting climate adaptation. Recent advancements in technology, such as remote sensing, data analytics, and simulation [21] are providing new opportunities for monitoring and managing water resources in a changing climate. However, these technologies are not yet available or accessible in many regions.

In this context, the purpose of the present study is to assess the influence of climate change on water supply and quality, focusing on Lake Powell in the United States. Lake Powell, located on the Colorado River, is one of the largest reservoirs in the United States. It is a crucial water source for millions of people in the region. sustaining agriculture, industry, and cities. Nonetheless, the reservoir has experienced considerable losses in water levels in recent years, mostly due to climate change-related factors such as decreasing snowpack, increasing evaporation rates, and longer droughts [22,23]. The fall in water levels has not only harmed the water supply, but also led to a decline in water quality, since contaminants and silt concentrations have increased.

This study utilizes a variety of current material, including scientific papers, environmental evaluations, and policy documents, to better comprehend the influence of climate change on Lake Powell's water resources. The study takes a mixed methods approach, combining the Vensim model and a predictive regression method in order to assess the present and future state of water supplies and propose feasible adaptation measures. This study contributes to a broader conversation on the effects of climate change on water supplies and the need for proactive adaptation measures to mitigate the adverse effects on human and environmental well-being. This research will ultimately inform policy and decision-making processes to ensure the sustainable use of water resources in response to climate change.

The structure of this paper is as follows: Section 2 addresses the methodology adopted for the study Section 3 discusses the findings from these studies and follows with conclusions and recommendations in section 4.

2. Methodology

2.1. Site Description: Lake Powell

Figure 2 depicts Lake Powell’s geographical overview, a man-made reservoir that delivers water to almost 40 million people in seven states: Arizona, Nevada, New Mexico, Colorado, Utah, California, and Wyoming [23]. Figure 3 illustrates Lake Powell map and has a total shoreline length of nearly 2000 miles, a depth of 400 feet, a length of 186 miles long, and a water storage capacity of 27,000,000 acre-feet. Lake Powell is vital because it supplies plentiful fresh water for drinking, irrigation, fishing, recreation, and energy production [23]. Colorado's snow-capped mountains and rivers including the Colorado, Escalante, San Juan, and Green are the principal water sources [9].

With the effects of warming temperatures on river stream flows and the growth in consumptive water usage in the basin [25], there has been increased concern about future water inflows. Several studies have looked at how projected future warming will affect streamflow in the Colorado River basin [25]. All these studies have found that future warming will have a significant negative impact on Colorado river stream flows. Figure 4 illustrates Lake Powell's height plunged to an incredible 3,535 feet above sea level in mid-August 2022, the lowest it has been since it was filled in 1980 [26].

Figure 5 is a time series of satellite images demonstrating the severe drought impact on Lake Powell in the twenty-first century. The lake is at a high level in the snapshot taken in 1999. Following more than two decades of drought, the Lake's water levels dropped dramatically in 2021, as depicted below. According to the U.S. Drought Monitor (USDM), the majority of the southwest has not only experienced drought in recent decades but is also transitioning to an amid climate [9]. Since 2000, river flows have been below average due to the southwestern North American megadrought, resulting in reduced lake levels. Lake Powell's water level has declined to the lowest known levels due to decreased runoff and river streamflow in recent decades, earlier snowmelt, and higher water demand. The most recent assessment of hydroclimatic trends in the Lake Powell region is presented in Table 2.

Table 1. The list of the top 10 countries most affected by the Climate Risk Index between 2000- 2019 (adopted [20])

CRI 2000-2019 (2000-2018)	Country	CRI Score	Fatalities	Annual Death Average/100,00 Inhabitants	Total losses (Million US$)	Losses/Unit GDP in %	Number of Events (2000-2019)
1(1)	Puerto Rico	7.17	149.85	4.12	4149.98	3.66	24
2(2)	Myanmar	10.00	7056.45	14.35	1512.11	0.80	57
3(3)	Haiti	13.67	274.05	2.78	392.54	2.30	80
4(4)	Philippines	18.17	859.35	0.93	3179.12	0.54	317
5(14)	Mozambique	25.83	125.40	0.52	303.03	1.33	57
6(20)	The Bahamas	27.67	5.35	1.56	426.88	3.81	13
7(7)	Bangladesh	28.33	572.50	0.38	1860.04	0.41	185
8(5)	Pakistan	29.00	502.45	0.30	3771.91	0.52	173
9(8)	Thailand	29.83	137.75	0.21	7719.15	0.82	146
10(9)	Nepal	31.33	217.15	0.82	233.06	0.39	191

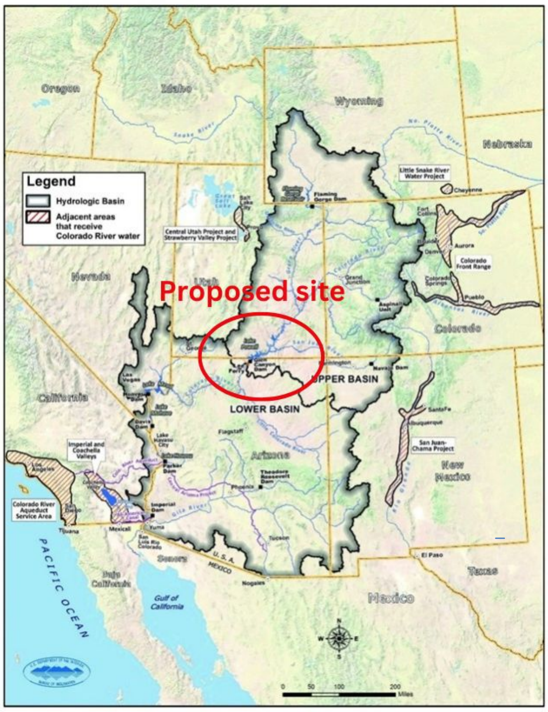

Figure 2. Map of Lake Powell (Image source: [30])

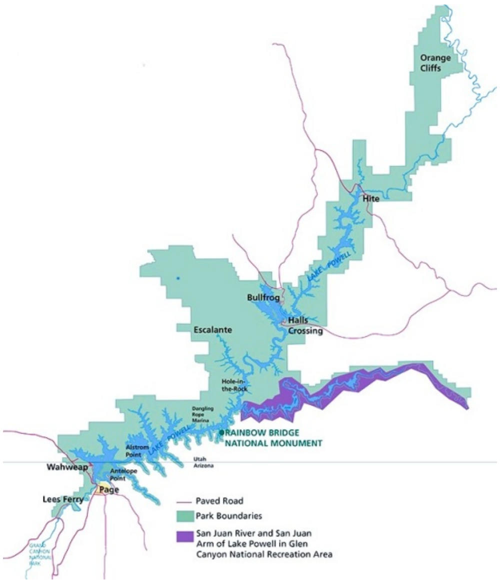

Figure 3. Maps of Lake Powell recreation areas (Image source: [24])

Figure 4. Lake Powell Elevation 1980 - 2022 [30]

According to NOAA, if Lake Powell's level continues to decline at the current rate, the states and 40 million people who rely on the water for drinking, agricultural and tribal water supply, and energy production could suffer a water deficit. Thus, the states have an enormous economic deficit. The 2020 economic impact of drought in six states due to climate change is presented in Table 3 [9].

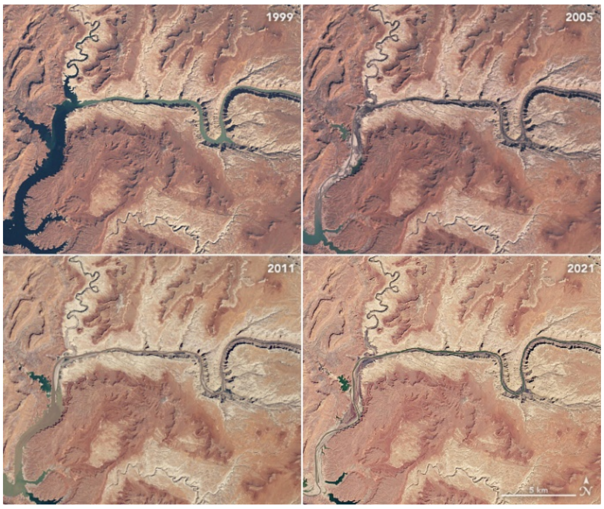

Figure 5. Water level in lake Powell Landsat series of satellites between 1999 and 2021 (Image source: [27])

Table 2. Summary of recent hydroclimate trends [9]

Variable	Trends Since the 1980s	Likely Causes
Temperature	Increasing	Anthropogenic climate change, natural variability
Precipitation	Decreasing	Natural variability, anthropogenic climate change
Snowpack water volume	Decreasing	Decreasing precipitation, warming temperatures
Timing of snowmelt & runoff	Earlier	Warming temperatures, dust-on-snow, decreasing precipitation
Annual Streamflow	Decreasing	Decreasing precipitation, warming temperatures

Table 3. Economic burden of drought in six states owing to climate change in 2020-2021

State	2021 Reservoir storage (%)	2020 Economic cost of drought ($ Million)
Arizona	51	5-100
California	58	250-500
Nevada	58	5-100
New Mexico	42	5-100
Utah	92	5-100
Colorado	84	250-500
Total	57	515-1.3B

Colorado River discharges are managed and operated in accordance with the "Law of the River," a combination of federal laws, agreements, and regulations. According to the US Bureau of Reclamation (USBR), this framework, established in 1922 by the Colorado River Compact, oversees the use and management of the river's water by the seven basin states and Mexico [28]. Lake Powell relies on numerous essential water management rules, including the Law of the River [28], Interim Guidelines [29], and Drought Contingency Plan [22].

2.1.1. Colorado River Compact 1922

In 1922, six of the seven Colorado River Basin states signed an intergovernmental agreement known as the

Colorado River Compact 1922 whose main function was to distribute the minimum amount of water from the upper basin states of Colorado, Utah, Wyoming, and New Mexico to Lake Mead and the lower basin states governs Lake Powell's operations. As per the agreement, the lower basin states allocate the following amounts each year: Arizona has a Million Acre-Feet (MAF) of 2.8, California has a MAF of 4.4, and Nevada has a MAF of 0.3. Whereas, according to the 1948 Upper Colorado River Basin Compact, the Upper Basin states (Colorado, New Mexico, Utah, and Wyoming) allocations are based on percentages of total available water, up to 7.5 MAFY. Colorado would get 51.75%, New Mexico 11.25%, Utah, 23% and Wyoming 14%. The US and Mexico agreed to a deal in 1944 that allocated Mexico's Colorado River apportionment based on a fixed quantity. As a result, Mexico receives the following amount per year: Mexico = 1.5 MAF. Since the early 1970s, the "minimum objective release" from Lake Powell to Lake Mead has been 8.23 MAF, which is distributed to meet water allocation criteria under the Law of the River.

2.1.2. Interim Guidelines 2007

The Interim Guidelines (2007) outline how Lakes Powell and Lake Mead will be managed based on specified reservoir elevation levels as shown in Tables 4 and 5. Importantly, the interim guidelines call for the two reservoirs to be operated in a coordinated way. If Lake Powell starts to become too low, for example, less water will be sent downstream to Lake Mead, helping to keep Powell's water levels stable. While these standards were created to improve system management and constitute a step forward in collaborative governance for the Colorado River, this coordinated management – known as "equalization" – makes it extremely difficult for Lake Powell to fully recover.

2.1.3. Drought Contingency Plan (DCP) 2019

By limiting their water usage and so preserving more water in rivers and reservoirs, the DCP allows all seven states to do their share to save water and protect the whole Colorado River system.

2.2. Data Analysis Methods

For this study, a regression method was implemented where data from the Lake Powell database was analyzed from 1964 to 2022 (Figure 6). We expected that the lake's temperature and geography would remain stable over the next few years and that the preceding decade's drought would persist. We assumed that historical trends were accurate and linear and that we could use them to predict the future of the lake. We used historical patterns rather than political agreements (such as the Colorado River Compact of 1922) to calculate outflow in our model; such agreements do not reflect actual climate (such as the recent drought). Aside from the fundamental characterization of existing datasets, no new research or quantitative analysis was conducted for this study.

Table 4. Lake Powell Operational Tier (Adopted: [30])

Lake Powell Operational Tiers
(*Subject to April adjustments or mid-year review modifications*)

Elevation (ft)	**Operational Tier**	**Active Storage (maf)**
3700	Equalization Tier	24.32
3,636-3,666	*equalize, avoid spills, or release 8.23 maf* Upper Elevation Balancing Tier	15.54-19.29
3,575	*Release 8.23 maf if Lake Mead< 1,075 ft* Mid Elevation Release Tier	2008-2026 9.52
3,525	*Release 7.48 maf if Lake Mead< 1,025 ft, release 8.23 maf* Lower Elevation balancing Tier	9.53
3,370	*Balance contents with a min/max release of 7 and 9.5 maf*	0

Table 5. Lake Powell operating table through Interim Guidelines (Adopted: [28])

Lake Powell Equalization Elevation Table	
Year	**Elevation (ft)**
2008	3,636
2009	3,639
2010	3,642
2011	3,643
2012	3,645
2013	3,646
2014	3,648
2015	3,649
2016	3,651
2017	3,652
2018	3,654
2019	3,655
2020	3,657
2021	3,659
2022	3,660
2023	3,662
2024	3,663
2025	3,664
2026	3,666

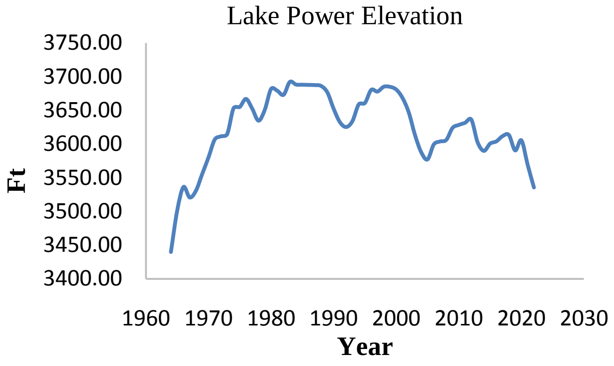

Figure 6. Lake Powell water elevation 1964 to 2022 [30]

Three moving average equations were generated for inflow, outflow, and storage. The inflow equation

$$Y = -1388.6x^2 + (5.505\times106)x - (5.453\times106) \quad (1)$$

The outflow equation

$$\begin{aligned} & -0.7x^5 + (6.99\times104)x^4 \\ Y = & -(27.95\times106)x^3 - (55.84\times109)x^2 \quad (2) \\ & +(55.77\times1012)x + (22.28\times1015) \end{aligned}$$

The storage equation

$$\begin{aligned} & -(0.6\times10-3)x^6 + (6.799)x^5 - (32861)x^4 \\ Y = & -(84.63\times106)x^3 - (122.47\times109)x^2 \quad (3) \\ & +(94.42\times1012)x + (30.3\times1015) \end{aligned}$$

$$Mean\ absolute\ deviation = \frac{1}{n}\sum_{i=1}^{n}\left|X - X_i\right| \quad (4)$$

Where n is the number of data values, x is the average dataset and x*i* is the original dataset. Mean absolute deviation provides variability of the dataset.

$$Mean\ square\ error = \frac{1}{n}\sum_{i=1}^{n}\left|X - X_i\right|^2 \quad (5)$$

Mean square error provides how dataset is close to regression line.

$$Root\ mean\ square\ error = \sqrt{\frac{\sum_{i=1}^{n}\left|X - X_i\right|^2}{N}} \quad (6)$$

Root mean square error simple refers to the standard deviation of prediction errors

$$Mean\ absolute\ percent\ error = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{X_i - X}{X_i}\right| \quad (7)$$

Mean absolute percent error measures how good a forecast system is.

The data for inflow, outflow and storage are regressed over time to show an existing ascending and descending trend. Understanding the relationship would help us determine how climate change affects water resources. From the 59 observations, R^2 for both outflow and storage are quite high but that of inflow is low in our forecast model compared to actual data. Prediction for inflow is quite difficult since it depends on the many uncertain parameters such as rainfall, snowfall, groundwater, and reservoirs. Complex hydrological processes and reservoir modelling are needed to model accurately the inflow of water. Outflow of water can be managed mainly by human activities. Consumption and utilization of water can be managed by policies. Moving averages were used to analyze the given data, forecast, and provide general idea of the trend. Parametric studies were done to select years for the moving average based on the mean absolute percent error. Mean absolute percent error for outflow and storage were less than 20% which means the model is good. The inflow model would need more improvement. An addressing situation is the high descending trend in the inflow of water which raises much concern for water resources security.

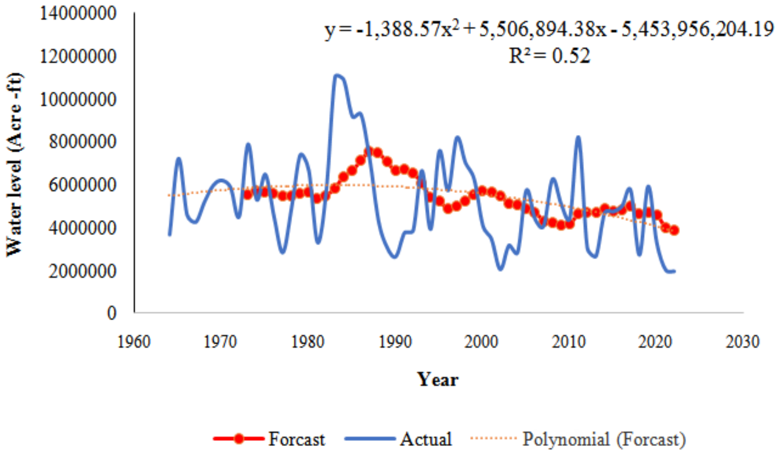

Figure 7. Predicted ten years Lake Powell inflow

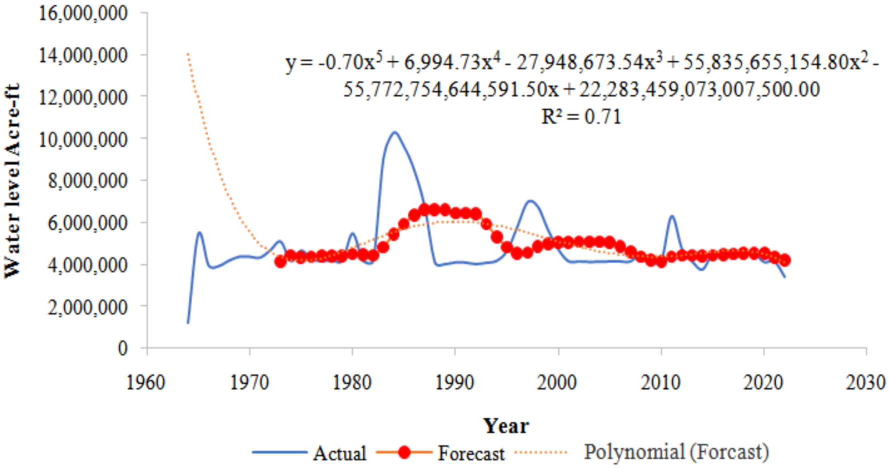

Figure 8. Predicted ten years Lake Powell outflow

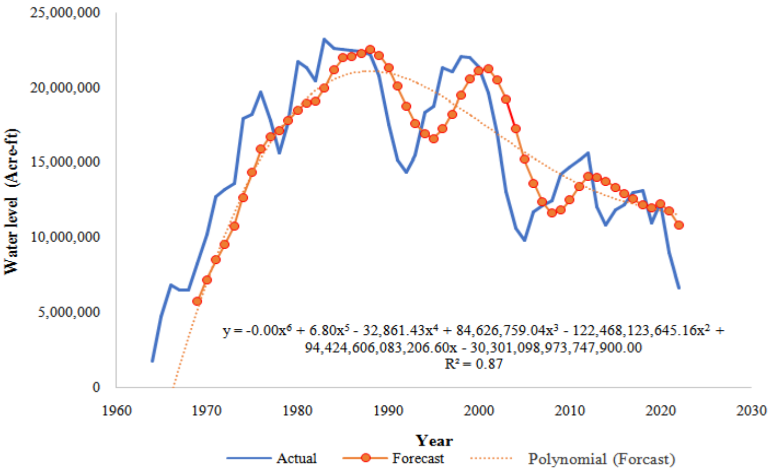

Figure 9. Predicted ten years Lake Powell storage

2.3. System Dynamic

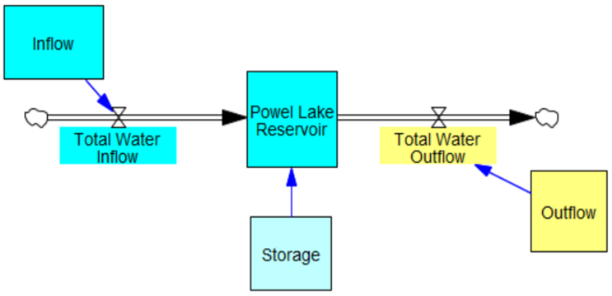

Figure 10. Lake Powell System Dynamic Stock and Flow Structure

System Dynamic (SD) model (Figure 10) was created to aid decision-makers in simulating and optimizing alternative solutions to water-related issues under various situations. Historical data analysis and forecast-based methodologies were utilized to simulate the dynamic behavior of water resource systems under various scenarios and measures in this assessment. As a result, a system dynamic simple model is implemented with a Lake Powell Reservoir as a stock and flow structure. Inflows, storage, and outflows as variables, and the reservoir is a stock. Water inflows are caused by rain, river discharges, and snowmelt, whereas outflows are caused by water consumption and losses.

The following equation is used to model the amount of water in the reservoir.

$$LakePowellReservior = Initialreservior(1964) + \int_{1964}^{2022} \left(inflow(t) - outflow(t)\right) dt \quad (8)$$

where inflow (t) and outflow (t) are the reservoir flow values at any time t between 1964 and the present time 2022.

Table 6. Summary of the data analysis

Data Analysis	Inflow	Outflow	Storage
Mean absolute deviation	1768917.02	1040735.5	2354972
Mean square error	3537834	2.375×10^{12}	8.157×10^{12}
Root means square error	1880.9	1541332.29	2856171.8
Mean Absolute percent error	0.424%	0.196%	0.169%
R^2	0.523	0.71	0.866

This simple model estimates the reservoir balance with inflows (precipitation, snow, and river discharge) minus outflows equals Lake Powell water level (total releases and evaporation). Total releases are linked to human, industrial, and agricultural use and should not be considered the primary driver of water level dynamics. The model, however, is not completely deterministic. The outflows from the Lake Powell reflect the release policy (i.e., Colorado River Compact, 1922) to meet the water demand.

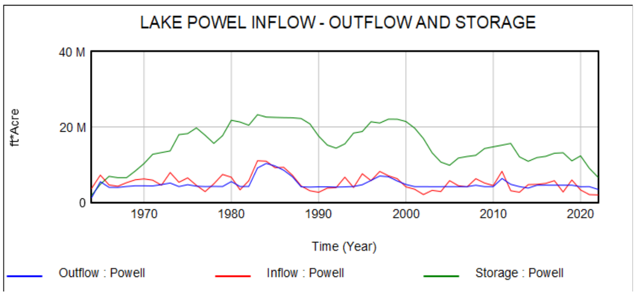

Figure 11. Lake Powel reservoir profile

The inflows are erratic and reliant on the weather, this increases the level of uncertainty in the modeling. There is no direct relationship between climate change and precipitation, snow, or evaporation. This model is implemented based on forecasts.

3. Results and Discussion

The study highlights the impact of climate change on water resources and the risk associated with it. The need to establish a water governance framework to harness and manage water resources is demonstrated in the Lake Powell case study. The governance framework will require a review of the existing allocation agreement. The exploration of options to index utilization to inflow should be studied and discussed with the stakeholders.

We produced the forecast results of Lake Powell's water reservoir from 2022 to 2040, as shown in Figure 12 based on the system dynamics of the water reservoir model. The total water level will gradually fall in the future and will be empty by 2035 if current trends continue. However, if consumption is reduced by 5 to 10%, the total water level in Lake Powell will be sustained beyond 2040 into the near future.

- Except there is a change in inflow rate, the reservoir will be depleted by 2036 at the present average consumption rate of 4.27Million ft. acre/year.
- A reduction in consumption rate by 5% below the 2021 rate will extend the reservoir beyond 2040.
- A reduction by 10% in consumption will retain over 4million ft acre of water in the reservoir in the short-term.

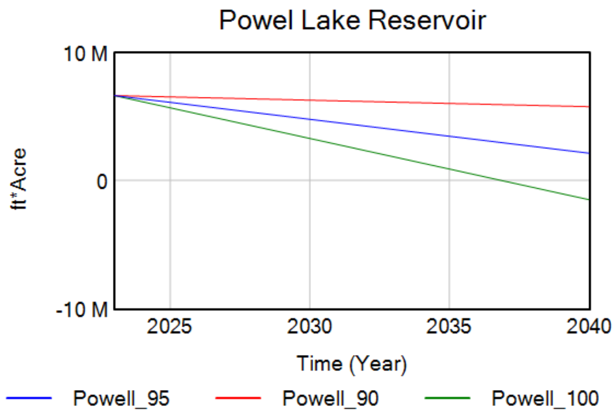

Figure 12. Lake Powell Reservoir Forecast

It is critical for water management authorities to strictly regulate Lake Powell water utilization. Meanwhile, because agricultural water use continues to account for most water utilization, increased investment in efficient irrigation technology and capacity are imperative to conserve the reservoir. The dynamics of Lake Powell's surface levels are driven by climate change, particularly local warming, and extreme weather, which includes both precipitation and temperature. Extreme weather, such as unusually high or low precipitation, affects changes in surface levels directly, and extremely high temperatures in recent decades have resulted in considerably more water loss through evaporation, which could be another factor. Since the 2000s, the rising temperature trend and megadrought have played a key role in water loss and, as a result, the decrease of Lake Powell surface levels.

This project also included simulation and scenario analysis of a water reservoir model for Lake Powell the next two decades. The following are the primary conclusions that were obtained. The regression method and system dynamic method's results show that water management is ineffective. The lack of predictability in water supplies is a fundamental challenge to water management in Lake Powell. While river water supply is already complicated by issues relating to the law of the river, a more recent concern to the water supply is increasing climate variability and rising climate change threats. More literature studies are needed to simulate climate change's implications on water resources, adapt to climate change, and understand the relationship between climate change and water resources.

4. Conclusion and Recommendations

4.1. Conclusion

The study sets out to investigate the impact of climate change on Lake Powell water resources. The increase in utilization and reduced inflow are attributed to the declining reservoir observed in Lake Powell. To fully understand the impacts of operating the lake at low levels, the study examines historical water demand trends, future demand forecasts, hydrological factors influencing water availability, and legal factors causing management uncertainty.

The study emphasizes a few key findings summarized as follows:

- Regional and localized models indicate that there are rising temperatures in various regions, decreased snow accumulation, and reduced annual runoff and streamflow.
- Discrepancies are observed between the areas where significant population centers are situated and the natural locations where the Colorado River supplies water.
- In the case of a localized shortage, many users who depend on Colorado River water face challenges in accessing alternative water sources.

Water conservation and management policy provide the tools necessary to sustain natural reservoirs such as Lake Powell. Lake Powell will benefit from a detailed scientific design policy to monitor and manage inflow retainment, water allocation, rainfall harvesting and wastewater management. Implementation of responsive water conservation and policy framework are effective tools to mitigate the impact of climate change on global water supply and quality. The policy should be reservoir-focused and address the concerns of the stakeholders using the resources. Responding to these pressures necessitates better consumption management (e.g., human consumption, land, and agriculture, energy production) and reducing CO2 emissions through efficient utilization of low-carbon, and low-energy-intensive technologies.

4.2. Recommendation

In the short term, there is a need to reduce water drawn from the reservoir to reflect the inflow magnitude, while long-term sustainable options are being investigated. Water agencies need to re-evaluate water demand assumptions, operating rules, and conduct contingency planning for existing water reservoirs, propose water-management systems adaptable to climatic variations that have previously been employed. A detailed reservoir model is recommended to monitor, manage, and sustain the reservoir. Explore alternate sources of water to reduce uncertainty, particularly those arising from reservoir operation, hydrological model structure, harvesting rainfall and runoff should be investigated in future research. Loss containment and rain harvesting strategies should be developed to reduce losses and increase inflow. Harvesting rainfall and channeling the water into the reservoir is one option to increase the inflow. Government agencies and departments should investigate options to develop broad base water conservation management strategies to sustain the surface water reservoirs. Public education on the declining water reservoir and encourage the voluntary reduction of water utilization from the reservoir.

The efficient utilization of water may reduce the impact of climate change. Eliminating leakage from water supply systems would help reduce water losses for utilization at homes and industrial purposes. An assessment of the water supply from Lake Powel is recommended.

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